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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A summary of research findings is presented on a project to study the use of Molecular Beam Epitaxy Techniques in metallization of semiconductors such as GaAs. Epitaxial metal layers of Nb and Ta have been grown on sapphire and overlayers of Ge, Au, Cu and Co have been deposited on (110) and (100) GaAs. The interfacial structure and defects have been studied using x-ray scattering and transmission electron microscopy.

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Statement of the Problem Studied under Grant DAAL03-86-G-0053

The major thrust of the research program was towards understanding the growth, structure, and electronic characteristics of thin films of metals and metal-semiconductor interfaces grown by Molecular Beam Epitaxy (MBE). This technology has advanced rapidly in recent years towards the deposition of epitaxial metals layers on semiconductors. It is a very promising technique because of the abrupt, high quality crystalline interfaces that can be achieved.

The ARO Fellowship, awarded to graduate student Frank Lamelas, has supported PhD dissertation research on the growth and characterization of thin film MBE heterostructures.

The problem of metallization carried out in the limit of ultra-thin films (10 Å to 100 Å) is one of the forefront concerns of microelectronics. The project has evaluated the growth conditions of several epitaxial metal layers on substrates such as sapphire and GaAs. The techniques of high resolution electron microscopy and x-ray diffuse scattering have been applied to improve our understanding of the interfacial structure resulting from MBE growth of metal layers on semiconductors.

List of Publications and Technical Reports
Resulting from ARO Grant
DAAL03-86-G-0053 (7/1/86 - 8/31/89)

Journal Publications

1. "The Characterization of Modulated Metallic Structures by X-ray Diffraction" R. Clarke, Proceedings of the Advanced Research Workshop on Thin Film Growth and Characterization, Brighton, Sept., 1986. NATO ASI Series B: Physics Vol 163 (Plenum, NY, 1987) p. 379.

2. "Time-resolved X-ray Scattering Study of Ordering Kinetics in $SbCl_5$-graphite" P. Hernandez, F. Lamelas and R. Clarke; P. Dimon, E. Sirota and S. Sinha, Physical Review Letters 59 1220 (1987).

3. "X-ray Diffraction Study of Epitaxial Nb/Ta Overlayers on Sapphire," F. J. Lamelas, H. He, and R. Clarke, Physical Review B38, 6334 (1988).

4. "Structural Fluctuations and Randomness in GaAs-$Al_xGa_{1-x}As$ Supperlattices," F. Lamelas, Superlattices and Microstructures 4, 371 (1988).

5. "Epitaxial Co-Au Supperlattices," C. H. Lee, Hui He, F. Lamelas, W. Vavra, C. Uher, and R. Clarke, Physical Review Letters, 62, 653 (1989)

6. "Coherent fcc stacking in epitaxial Co/Cu superlattices," F. Lammelas, C. H. Lee, H. He, W. Vavra and R. Clarke, Phys. Rev. B40 5837 (1989).

PhD Thesis

"Growth and Structural characterization of Epitaxial Metal Layers on GaAs," F. J. Lamelas University of Michigan Thesis, 1989.

Personnel Supported

F. J. Lamelas, Graduate Student Research Assistant

Summary of Research Findings

Transition Metals on Sapphire

The first phase of the project concerned the growth of epitaxial thin films of transition metals on insulating substrates. Sapphire was chosen as the most straightforward system to study first since it has already been demonstrated that this substrate is promising for the epitaxy of refractory metals. In particular, Nb and Ta have both been grown epitaxially on polished sapphire using MBE techniques.

We have grown films of Nb and Ta on sapphire which has been cut and polished in the 1120 crystallographic direction. The films were approximately 5,000 Angstroms thick and were grown at various substrate temperatures in order to determine the optimum growth temperature.

The crystallographic quality of the films was characterized using x-ray diffraction methods. A diffractometer configured in the four-circle geometry was used for this purpose. This method had the advantage that both the quality of the layering (atomic smoothness) and the degree of epitaxial ordering could be determined simply by taking two x-ray diffraction scans, one with the diffraction vector normal to the layers and one at right-angles to this.

In-plane diffractometer scans on the as-grown films confirmed that a substrate temperature of 850 C was optimum for both Nb and Ta. The films are entirely single-crystal and oriented in the (110) direction when grown at this temperature. Lower substrate temperatures, e. g. 750 C, result in poorer quality structure.

An interesting and potentially useful finding is that good lattice matching with the substrate does not seem to be a requirement in order to have single-crystal film growth. Apparently, the crystallographic vectors of the metal film orient themselves in the plane of the substrate so that the strain energy at the interface is minimized. Because the lattice parameters of the metal and the sapphire bear no obvious relationship to each other the angle at which the strain energy is minimized does not correspond to one of the usual interaxial angles of either structure. In all of the samples grown to date this angle is, however, reproducible. The results have implications for making epitaxial contacts to semiconducting materials where coherent structure will be important in reducing contact resistance.

Au on GaAs

A second thin film project concerns growth of epitaxial gold films on GaAs for improved ohmic contacts. This project is in collaboration with Dr. Ken Jones of EDTL, Fort Monmouth. A series of 600 Å gold films have been grown on 100 GaAs substrates at different temperatures (ambient, 100 C, and 200 C). The optimum temperature of theses seems to be ambient temperature; we observe significant diffusion into GaAs at the higher temperatures. Our high-resolution x-ray diffractometer scans show the epitaxial relationship to be Au (110): GaAs (100), for which a close lattice match exists.

The effect of (110) GaAs substrate orientation was also studied. Streak-like RHEED patterns indicate epitaxial growth. We have noted a tendency of the Au-film to take up a (111) growth habit on the (110) substrate orientation, even though it commences growing in the lattice-matched (110) orientation. The crossover to (111) growth occurs with the first 20 Å of growth. Growth conditions for Ge-buffer layers are 500° C at approximately 1 Å sec^{-1}, with pre-cleaning of the GaAs surface by heating to 600° C for 30 minutes.

Pronounced RHEED streaks from the GaAs surface (before growth begins) appear after 5 minutes heating to 600° C, indicating that the surface is atomically smooth prior to growth. Growth rates for Au (from a K-cell) are 0.1 - 0.2 Å sec^{-1} with the substrate held at 50° C.

Magnetic Layers on GaAs: Co Epitaxy

The use of Ge and Ge/Au as a metallizing layer on GaAs, has been explored in a number of different substrate orientations. The epitaxy of Cu on GaAs (110) has been achieved by inserting very thin (20 Å) layers of Co. The Cobalt layers act as a bridge between the Ge/GaAs and the fcc structure of Cu. The Co layers are found to be in the bcc metastable phase.

In the last phase of the project, the work has been extended to growth of metallic magnetic superlattices on GaAs. Epitaxial superlattices of Co-Au and Co-Cu have been successfully grown on 110 GaAs. The results are reported in two papers accepted recently in Physical Review.